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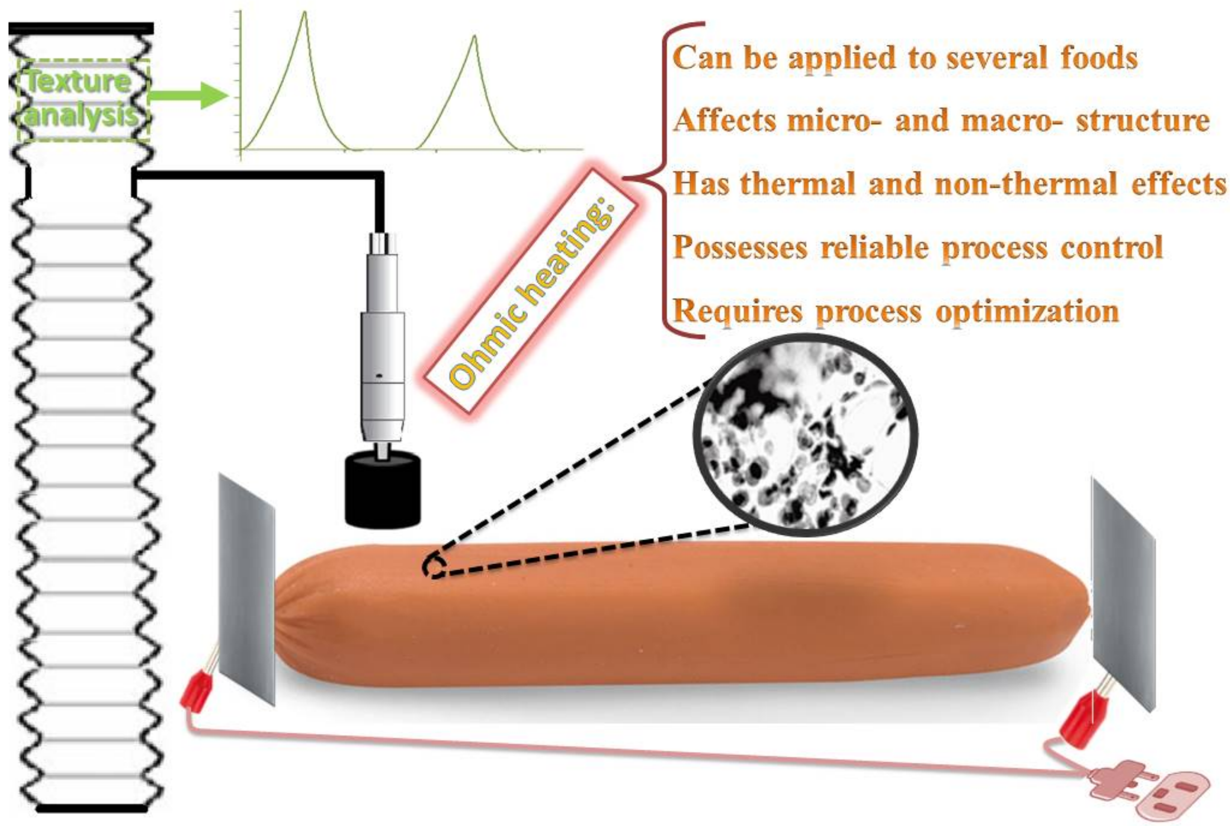
Texture analysis
Ohmic heating:
Can be applied to several foods
Affects micro- and macro- structure
Has thermal and non-thermal effects
Possesses reliable process control
Requires process optimization

Food texture as affected by ohmic heating: Mechanisms involved, recent findings, benefits, and limitations

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Abstract

Background

Food texture is an important quality characteristic that affects sensory perception and consumer satisfaction. Thermal processing applies to food material for several reasons including palatability improvement and shelf life extension. Ohmic heating is an energy- and time-saving technique that was previously proposed as an alternative to conventional heating methods in the food industry.

Scope and approach

Investigating the effect of ohmic heating method on food quality parameters, such as texture, is an important step towards the industrial adaptation of ohmic heating. This review focuses specifically on the effects of ohmic heating on food texture and tries to elucidate the mechanisms behind the changes in textural attributes during an ohmic process as compared to the classical heating method.

Key findings and conclusions

Achieving a predefined product texture in a shorter time and the uniformity of product texture are among the benefits of ohmic heating. However, several challenges including operator safety, negative effect on the chemical composition of the product and high capital investment need to be addressed for the industrial adoption of this technology.

Keywords:

food texture; hardness; ohmic heating; moderate electric field; emerging technologies; food quality.

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1. Introduction

Thermal processing has a long history in food production and still has many applications in food industries. This process involves applying thermal energy to food materials for several purposes such as cooking, extraction, enzyme inactivation, and microbial decontamination (Pankaj, 2016). Although the classical heating method, which relies on conduction and convection modes of heat transfer, is still the most popular heating technique in the food industry, emerging techniques, such as ohmic heating, have been proposed as potential energy-saving alternatives to the time- and energy-intensive conventional methods. Ohmic heating is defined as a process wherein an alternating electrical current passes through a conductor and the flowing charges result in temperature increase according to the Joule's law. In food processing, the conductor could be any food material with sufficient electrical conductivity. Unlike the conventional heating methods which rely on transferring heat from a heating surface, ohmic heating generates heat volumetrically inside the material and can raise the temperature at a higher rate. Several parameters affect the heating rate in an ohmic process including instrumental and food material specifications. Figure 1 represents the schematic of a batch ohmic heater and the basic elements of this equipment. The power supply provides the electric energy, with predefined specifications, for the process. The voltage and frequency of the electric current are among the parameters determining the heating rate. The electrical energy applies through two electrodes which are located on both sides of the heating chamber and are in direct contact with food materials. The contact area of the electrodes with food material and the distance between these electrodes also influence the heating rate. The heating rate also depends on the food characteristics which determine its electrical conductivity, such as food chemical composition, physical state, and temperature. Moreover, any change in the physical state of food materials, such as starch gelatinization, protein denaturation, and water evaporation, during the thermal process can affect the heating rate in an ohmic process. It should be noted that other parameters, such as material flow rate, number of electrodes and their positioning, can also influence the ohmic heating rate in a continuous ohmic heating process,. Although this innovative heating technique is still in its infancy in the food processing sector, numerous research has been conducted on its potential application for cooking (Jittanit, Khuenpet, Kaewsri, Dumrongpongpaiboon, Hayamin, & Jantarangsri, 2017; Wang & Farid, 2015; Kanjanapongkul, 2017), sterilization (Park, Balasubramaniam, Sastry, & Lee, 2014), pasteurization (Achir et al., 2016; Cho, Yi, & Chung, 2017; Dima, Istrati, Garnai, Serea, & Vizireanu, 2015), blanching (Gomes, Sarkis, & Marczak, 2018; Bhat, Saini, & Sharma, 2017), extraction (Aamir & Jittanit, 2017; Gavahian, Farahnaky, Farhoosh, Javidnia & Shahidi, 2015; Gavahian, Farahnaky, Javidnia, & Majzoobi, 2012; Gavahian & Farahnaky, 2018; Gavahian & Chu, 2018) and drying (Moreno, Espinoza, Simpson, Petzold, Nuñez, & Gianelli, 2016; Zhong and Lima, 2003). These studies revealed that ohmic heating is superior to the conventional method in terms of saving process energy and time. However, the effect of the above-mentioned ohmic processes on the overall product quality should be investigated prior to industrial adaptation of this technique. Although various definitions have been suggested for the term “food quality”, a large contributor to the quality of a product is its texture, i.e., the sensation the food imparts to the mouth as the food is bitten, chewed and swallowed (Rosenthal, 1999; Apaiah et al., 2005). The process conditions can influence the product texture and its acceptability by consumers (Apaiah et al., 2005). The volumetric nature of ohmic heating shortens the process time and enhances the heating rate which can yield a product with different textural properties from those of conventional heating methods. Therefore, the objective of this study is to overview the observations on the effects of

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ohmic heating on food texture to elucidate the involved mechanisms and to explore the benefits and limitations of this innovative heating technique. In this regard, a comprehensive literature search was carried out on previously conducted studies using scientific databases including “Web of Science”, “Scopus”, “PubMed”, “SciELO” and “ScienceDirect”. No limitation was applied in terms of the research period. The combined terms used in this work include: “ohmic” AND “ohmic heating” AND “ohmic cooking” AND “ohmic treatment “AND “ohmic process” AND “resistance heating” AND “electrical heating” AND “Joule heating” AND “texture” AND “firmness” AND “hardness” AND “springiness” AND “cohesiveness” AND “gumminess” AND “chewiness” AND “resilience” AND “Warner-Bratzler” AND “shear force” AND “Shear Tests” AND “Deformation” AND “Cutting Tests” AND “yield strength” AND “compression” AND “gradient “AND “texture profile analysis” AND “TPA”. The title and the abstract of the resulted papers were extracted and examined by the first author of the present study to exclude the papers that did not comply with the inclusion criteria. The exclusion process was then continued by studying the full text of the selected papers from the previous step to verify their appropriateness according to the inclusion criteria. This process was double checked with the last author of this paper. The opinion of other authors of the present study was asked in case of discrepancy. Besides, the references list of the retrieved surveys was reviewed to identify any further related sources. The selected articles were then de-duplicated and organized using version 1.19 of the Mendeley reference manager software (Elsevier, Netherlands). The inclusion criteria in the present work were original research/ scientific studies with an accessible full-text that were published in English and explored the effects of ohmic heating on the textural propensities of foods.

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2. Mechanism of textural softening in an ohmic process

During an ohmic heating treatment, the power supply provides an alternating electrical current which passes the feed mixture (Figure 1). The food materials act as a resistor and their temperature increase based on the Joule effect (Ramaswamy, Marcotte, Sastry, & Abdelrahim, 2014). Temperature increase can affect the micro- and macro-structures and result in several phenomena including moisture migration, starch gelatinization, and protein denaturation (coagulation and precipitation), depending on the process condition and treated material composition. Besides, non-thermal effects of ohmic treatments should be taken into account, especially when a low-frequency alternating current is applied to food materials (Sensoy & Sastry, 2004; Gavahian, Chu, & Sastry, 2018). Non-thermal effects of ohmic heating, including electroporation and electrical breakdown, were shown to alter the cells and tissues of some food materials. The extent of these phenomena in an ohmic process depends on the food material characteristics and process conditions such as process temperature, applied frequency, and the voltage gradient (Gavahian, Chu, & Sastry, 2018). According to the previous studies, low frequency and elevated electric field strength enhance the pore formation and electrical breakdown of the cells (Sensoy & Sastry, 2004; De Vito, Ferrari, Lebovka, Shynkaryk, & Vorobieval., 2008). In addition, fresh materials are more sensitive to the non-thermal effect of ohmic treatment than the previously damaged ones, i.e. the materials that were subjected to other processes, such as drying, prior to ohmic treatment (Sensoy & Sastry, 2004; Gavahian, Chu, & Sastry, 2018). Both thermal and non-thermal effects of ohmic treatment may be involved in textural changes of a food material (Allali, Marchal, & Vorobiev, 2010; Moreno, Simpson, Estrada, Lorenzen, Moraga, & Almonacid, 20118). However, high temperatures and Joule effect can overshadow the non-thermal effects of ohmic heating, especially when the process is performed at an elevated temperature (Gavahian, Chu, & Sastry, 2018; Gavahian & Farahnaky, 2018) such as in cooking and sterilization processes.

3. Ohmic processing and food texture

A wide range of textural changes occurs during ohmic heating following the microscopic and macroscopic changes of food materials. Food characteristics, such as electrical conductivity, and ohmic treatment conditions, such as the applied electric field, are among the determining parameters for the type and extent of these changes. Depending on the aim of the ohmic process, intense or slight textural changes could be desirable. While several processes, such as baking and cooking, involve a great amount of changes in textural properties, others aim to minimize textural changes. For example, minimum textural changes might be preferred in the blanching and sterilization processes of some fruits and vegetable products. Researchers investigated the textural changes of several commodities, including fruits (Allali, Marchal, & Vorobiev, 2010; Moreno, Espinoza, Simpson, Petzold, Nuñez, & Gianelli, 2016; Moreno, Simpson, Estrada, Lorenzen, Moraga, & Almonacid, 2011; Olivera, Salvadori & Marra, 2013; Pham, Jittanit & Sajjaanantakul, 2014), vegetables (Eliot-Godéreaux, Goullieux, & Pain, 1999; Eliot-Godéreaux, Zuber, & Goullieux, 2001; Wongsa-Ngasri & Sastry, 2016; Icier, Cokgezme, & Sabanci, 2017; Bhale, 2004; Farahnaky, Azizi & Gavahian 2012; Kamali & Farahnaky, 2015; Olivera, Salvadori & Marra, 2013), surimi (Moon, Yoon & Park, 2017; Fowler & Park, 2015; ark, Yongsawatdigul & Kolbe, 1998; Yongsawatdigul, Park, Kolbe, Dagga, & Morrissey, 1995; Pongviratchai & Park, 2007; Chai & Park, 2007), rice (Gavahian, Chu, & Farahnaky., 2019; ittanit, Khuenpet, Kaewsri, Dumrongpongpaiboon, Hayamin & Jantarangsri, 2017; Yang, Chen, Sun, Li, & Liu, 2006), cheese (Kumar & Hausain, 2014), tofu (Wang, Li, Tatsumi, Liu, Chen, & Li, 2007), fish

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(Matsubara, Tanaka, Narita, & Seki, 2007; Boonpupiphat, Khukutapan, & Jittanit, 2014), shrimp (Lascorz, Torella, Lyng & Arroyo, 2016), bakery (Maki, Yamaki, Tanaka, & Tanaka, 1998; Luyts, Wilderjans, Haesendonck, Brijs & Delcour, 2013), and meat products (Chiu, 2002; Vasanthi, Venkataramanujam, & Dushyanthan, 2007; Icier, Izzetoglu, Bozkurt & Ober, 2010; Piette et al., 2004; Shirsat, Brunton, Lyng, & McKenna, 2004; Özkan, Ho & Farid, 2004; Zell, Lyng, Cronin & Morgan, 2009; Zell, Lyng, Cronin & Morgan, 2010; Bozkurt & Icier, 2010; Dai, Zhang, Wang, Liu, Li & Dai, 2014; Tian et al., 2016; Icier, Sengun, Turp & Arserim, 2014; Engchuan, Jittanit & Garnjanagoonchorn, 2014), during ohmic heating (Table 1) and compared the observations with other processing methods including steam (Zell, Lyng, Cronin & Morgan, 2009; Lascorz, Torella, Lyng.& Arroyo, 2016; Bozkurt & Icier, 2010; Wang, Li, Tatsumi, Liu, Chen & Li, 2007), water bath (Dai, Zhang, Wang, Liu, Li & Dai, 2014; Boonpupiphat, Khukutapan, & Jittanit, 2014; Park, Yongsawatdigul & Kolbe, 1998), plate (Özkan, Ho & Farid, 2004), and microwave heating (Icier, Cokgezme & Sabanci, 2017; Farahnaky, Azizi & Gavahian 2012; Kamali & Farahnaky, 2015). They also used several textural evaluation techniques such as texture profile analysis (TPA) (Farahnaky, Azizi & Gavahian 2012; Allali, Marchal & Vorobiev, 2010; Icier, Cokgezme & Sabanci, 2017; Moreno, Simpson, Estrada, Lorenzen, Moraga & Almonacid, 2011; Shirsat, Brunton, Lyng, & McKenna, 2004), Warner–Bratzler (Zell, Lyng, Cronin & Morgan, 2009; Dai, Zhang, Wang, Liu, Li & Dai, 2014), torsion failure tests (Yongsawatdigul, Park, Kolbe, Dagga & Morrissey, 1995), or torsion gelometer (Chai & Park, 2007) to study the textural changes during the ohmic treatment.

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3.1 Fruits and vegetables

Ohmic heating of cauliflower revealed that sample history and possible pretreatments prior to ohmic heating can affect the final textural properties of the product (Eliot-Godéreaux, Goullieux & Pain, 1999). According to the authors, pre-heating florets in salted water enhanced the product firmness. The authors pointed out that a combination of ohmic heating and low-temperature preheating in salted water makes the high-temperature short-time sterilization of cauliflower florets feasible (Eliot-Godéreaux, Goullieux & Pain, 1999). In a similar study, the feasibility of continuous ohmic sterilization of cauliflower was assessed by Eliot-Godéreaux, Zuber & Goullieux (2001). The authors pointed out that ohmic heating can enhance the textural properties of the final product due to rapid uniform heating of materials. According to the authors, cauliflower, as a brittle vegetable, cannot stand the conventional heating sterilization but a sterilized product with acceptable firmness (compression force of 65-85% of its initial value) was obtained following an ohmic sterilization process. The authors also mentioned that larger florets withstand the ohmic process condition better than the small ones (Eliot-Godéreaux, Zuber & Goullieux, 2001). According to observations of these researchers, ohmic heating could be considered as a suitable alternative to conventional sterilization method for fragile products in terms of textural properties of the processed product. In addition, this research clearly showed that selecting appropriate raw materials can improve the overall textural quality of the ohmically sterilized food.

Farahnaky, Azizi & Gavahian (2012) investigated the effects of ohmic heating at low and high input powers using two different voltages (220 V and 380 V) on textural properties of several root vegetables, including red beet, carrot, and golden carrot, and compared the results with those of conventional and microwave cooking methods. TPA data showed that ohmic heating resulted in greater softening rates (Figure 2) and yielded a product with a lower hardness as compared to those of conventional and microwave products. The authors also reported that increasing the ohmic power (i.e. input voltage) accelerated the kinetics of textural softening of the studied vegetables and proposed this volumetric heating technique as an accelerating textural softening method (Farahnaky, Azizi & Gavahian 2012). In a similar study, textural properties of ohmically cooked cabbage, radish, turnip, and potato were compared to those of microwave and conventionally cooked samples using TPA (Kamali & Farahnaky, 2015). The authors observed a greater textural softening rate follow the ohmic cooking, as compared to that of conventional and microwave methods. In addition, this study revealed the type of raw material can affect the kinetic of textural softening in an ohmic process. The textural study of the ohmic treated samples showed that radish and cabbage experienced the highest and the lowest textural softening rates, respectively (Kamali & Farahnaky, 2015). Similar results were reported by Farahnaky et al. (2018) when turnip, kohlrabi, radish, and potato were cooked by ohmic heating (Farahnaky, Kamali, Golmakani, Gavahian, Mesbahi & Majzoobi, 2018). Therefore, the optimum ohmic process condition can vary, depending on the type of raw material. In a like manner, Olivera, Salvadori & Marra (2013) assessed the effects of ohmic heating on textural properties of potato, carrots, and apples at the frequency of 50 Hz and constant voltage gradients of 1.1, 2.2 and 3.3 kV/m. According to the authors, the firmness of the studied samples decreased with voltage gradient and treatment time. In addition, they reported that a minimum voltage gradient of 2.2 kV/m is required to achieve a desirable firmness in the final product. Moreover, they found that different materials may show different behaviors and sensitivities during an ohmic treatment. Apple was the most sensitive sample to the softening effects of ohmic treatment as compared to potato and carrot. This study showed that ohmic treatment can alter the textural properties of

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several fruits and vegetables, even those with low electrical conductivities, provided that they are immersed in an electroconductive medium.

The thermal process can be used as a peeling technique for vegetables such as tomato. Wongsa-Ngasri and Sastry (2016) proposed ohmic heating for tomato peeling in a lye solution. According to the authors, the electric field intensity and the chemical composition of peeling medium influenced the texture of the peeled tomato. Ohmic peeling of tomato in NaCl/NaOH and NaCl/KOH solutions improved the firmness of the product as compared to that of plain NaCl solution. They reported that incorporation of 2% $CaCl_2$ in the post-treatment solution and adjusting the electric field strength can enhance the peeled tomato quality. The results also showed that product firmness can be improved by a post-peeling ohmic treatment (Wongsa-Ngasri & Sastry, 2016). This study showed that both the process and post-process conditions can affect the texture of an ohmic-treated sample. Therefore, the desired texture could be achieved through optimization of both process and post-process parameters, including the process time, applied electric field strength, and concentrations of different ions in the product or its surrounding medium.

The effects of vacuum impregnation and ohmic pretreatments on textual properties of apple cubes were studied by Allali, Marchal & Vorobiev (2010). According to the TPA data, the product firmness was affected by ohmic treatment and dropped steeply from 20 N to 3 N due to thermal and non-thermal, i.e. electroporation, effects of ohmic treatment. In addition, incorporation of citric acid enhanced the electrical conductivity and resulted in greater changes in the product structure. These observations highlighted the importance of process optimization in an ohmic treatment to achieve desired textural properties. Likewise, a study on the combination of ohmic heating and vacuum impregnation prior to drying of folate-fortified apple snack revealed that vacuum impregnation/ohmic treatments enhanced the firmness of the product (Moreno, Espinoza, Simpson, Petzold, Nuñez & Gianelli, 2016). Samples were subjected to vacuum impregnation and ohmic treatment (electric field strength of 13 V/cm and frequency of 60 Hz at 50 °C) had a higher firmness (17.7 N) as compared to the ones that were only subjected to vacuum impregnation (10.6 N). In addition, the authors reported that impregnating the sample by vacuum impregnation and ohmic heating enhanced the folic acid content of the final product due to the electropermeabilization which allows some of the folate molecules to enter the fruit cells and withstand the drying condition. The authors concluded that textural changes following the ohmic treatment can enhance both physical and nutritional quality of the product. They also showed that ohmic treatment conditions, including the process temperature, can affect the mechanical properties of the product. A study on the effect of a low-temperature ohmic heating (50 °C) at the electric field strength of 13 V/cm on osmotic dehydration kinetics of apples showed that ohmic treatment affected the microstructure, cell walls and tissues of the apples through electroporation phenomenon (Moreno, Simpson, Estrada, Lorenzen, Moraga & Almonacid, 2011) and enhanced the leaching of cellular materials. According to TPA results, ohmic treatment slightly enhanced the firmness of samples which could be related to the leaching of the cell constitutes and dehydration of the apple cubes mainly due to the non-thermal effects of the ohmic process. The non-thermal effects of the ohmic treatment on microstructures were comprehensively discussed elsewhere (Gavahian, Chu & Sastry, 2018).

TPA of the ohmic treated carrot cubes at a constant voltage of 120 V, applied frequencies of 1 Hz and 60 Hz, and the endpoint temperature of 40 °C showed that ohmic treated samples had similar textural properties to that of untreated samples immediately after ohmic treatment. However, the hardness and fracturability of the ohmic-treated carrots were lower than the untreated ones after six days of storage at the relative humidity of 56%. These textural values were significantly smaller for the low-frequency treated sample (Bhale, 2004). The non-thermal effects of ohmic heating could be considered as the possible reason for this variation in the textural properties of carrot cubes during storage time as it could facilitate the components migrations to be diffused in and out of the carrot cell structures. It was previously illustrated that lowering the applied frequency of ohmic treatments can cause electroporation and affect the cell structures of fresh vegetables (Sensoy & Sastry, 2004; Gavahian, Chu & Sastry, 2018).

Pham, Jittanit & Sajjaanantakul (2014) proposed indirect ohmic treatment of ready-to-eat pineapple (inside a polypropylene package), as a minimal process, to reduce the textural changes during storage. According to the TPA data, changes in the firmness value of ohmic processed samples were significantly lower than that of the control sample (fresh pineapple) which could be related to enzyme inactivation by ohmic heating. Icier, Cokgezme & Sabanci (2017) investigated the feasibility of ohmic thawing of potato cubes and compared the results with microwave thawing methods. TPA results revealed that the firmness of the ohmic-thawed blanched potato cubes was almost two times greater than that of microwave process (2.8 vs. 1.4 kg, respectively) while there was no significant difference between the firmness of the ohmic- and microwave-thawed non-blanched samples. According to the study, pretreatments and raw product conditions can affect the degree of textural softening in an ohmic process (Icier, Cokgezme & Sabanci, 2017).

3.2 Meat products

Ohmic heating is a superior technique compared to the traditional meat thawing method in terms of time-saving. The effect of ohmic heating on the textural properties of frozen beef cuts showed that ohmic thawing results in a product with a higher hardness and lower springier than that of the conventional method. The authors reported that the applied voltage gradient affects the textural properties of the defrosted beef (Icier, Izzetoglu, Bozkurt & Ober, 2010). Both thermal and non-thermal effects of ohmic heating could be involved in meat thawing process and the variations in the final texture of the ohmic-thawed product should be taken into account by meat industries that wish to use this technique in their production lines.

Chiu (2002) studied the kinetics of textural changes in a ham emulsion during an ohmic cooking process at the applied voltages of 40-100 V, target temperatures of 60, 70 and 80 °C, and the holding times of 0, 20 and 30 minutes. According to TPA results, higher temperatures, shorter come-up times, and longer holding times resulted in a softer texture. In addition, ohmically cooked hams had a softer and chewier texture than the conventionally processed sample. Thermal treatment conditions such as process temperature and duration affect the texture of meat products (Vasanthi, Venkataramanujam, & Dushyanthan, 2007). Besides instrumental specifications, several parameters, such as electrical conductivity affect the heating rate in an ohmic process of meat. Thermal processing alters the meat structure through cell membrane destruction, muscle fibers shrinkage and protein denaturation, aggregation and gel formation as well as connective tissue shrinkage and solubilization (Yildiz-Turp, Sengun, Kendirci, & Icier, 2013).

Piette et al. (2004) cooked the bologna emulsion by ohmic heating and reported that the final product has different textural properties as compared to that of the traditionally processed product. According to the result, the ohmic product was softer, less cohesive, and less resilient than smokehouse product. The authors mentioned that the softer texture of sausage can be more pleasant for some food consumers, i.e. the ohmic processed sausage had a better textural property than the traditional one. They also pointed out that a harder texture, if desired, can be achieved by adjusting the product formulation. In a similar study, ohmic cooking of frankfurters yielded a product with a lower springiness which suggested a less elastic, mushier structure, according to the reported TPA (Shirsat, Brunton, Lyng, & McKenna, 2004). On the other hand, Özkan, Ho and Farid (2004) reported that ohmic cooking of burger patties yielded a product with similar textural properties to that of cooked by classical methods. Therefore, process condition and raw material specifications can determine the similarity degree between the ohmic- and traditionally-treated samples.

Zell, Lyng, Cronin & Morgan (2009) observed higher Warner–Bratzler peak load values for ohmically cooked beef muscles than the steam cooked ones, which means that ohmic heating yielded a product with a tougher texture than the conventional process. This indicates that cooking beef by ohmic heating can increase the product toughness. This research also revealed that pretreatments prior to ohmic process not only affect the textural characteristics of the ohmic treated product but also affect the textural uniformity. For example, increasing tumbling time increased the tenderness of the ohmic cooked beef. In addition, salt distribution within the product was affected by the pretreatment method and determined the heating uniformity (Figure 3). Salt injection technique and three hours tumbling both left the surrounding area of the meat uncooked. On the other hand, a uniform heating rate was observed for a two-day soaked sample in the salted water. Therefore, appropriate pretreatments might be required to enhance the textural uniformity of ohmic treated products.

Ohmic heating of the porcine *longissimus dorsi* increased the Warner-Bratzler shear force of the product as compared to that of the conventional water bath heating method. The authors also reported that increasing the end point temperature enhanced the Warner-Bratzler shear force of both ohmically and conventionally treated samples in two separated steps (from 20 to 40 °C, and then from 60 to 80 °C). The authors pointed out that the first increases were related to the connective tissue denaturation and the latter ones were mainly because of the myofibrillar proteins denaturation, intramuscular collagen and actomyosin shrinkage (Dai, Zhang, Wang, Liu, Li & Dai, 2014). In a similar manner, texture study by a texture analyzer equipped with a Warner–Bratzler shear attachment revealed that replacing conventional heating by ohmic heating cooking can increase the firmness of the cooked ground beef (Bozkurt & Icier, 2010). Likewise, the firmness of the turkey meat increased when ohmic cooking performed at the high-temperature-short time condition (95 °C for 8 min) instead of low-temperature long time steam processes (72 °C for 15 min) (Zell, Lyng, Cronin & Morgan, 2010). Ohmic heating generates heat volumetrically within the electroconductive material and minimizes the temperature gradient along the sample. On the other hand, conventional heating methods rely on classical modes of heat transfer from a heating surface which result in the non-uniform heating of the product (Ramaswamy, Marcotte, Sastry & Abdelrahim, 2014). It was reported that uniform heating during the ohmic process can result in collagen shrinkage and a meat product with a higher toughness can be expected following an ohmic heating process, as compared to that of the conventional heating method (Bozkurt & Icier, 2010; Yildiz-Turp, Sengun, Kendirci, & Icier, 2013).

Tian et al. (2016) investigated the effects of ohmic cooking on shear force value of beef muscle and compared the results with that of the traditional water bath cooking. The ohmic cooked product had a lower shear force value, as compared to that of the traditional method (5.6 kg). In addition, increasing the ohmic process voltage gradient from 3.3 V/cm to 12 V/cm decreased this textural parameter from 4.3 to 4.8 kg. According to the result, ohmic cooking can increase the tenderness of beef muscle, as compared to the water bath cooking method. The author pointed out that the higher intensity ohmic process yielded a product with the lowest shear force value due to the rapid heating rate, which provides limited time for denaturation and aggregation of muscle fibers and connective tissues.

Ohmic cooking enhanced the yield stress of pork meatballs, as compared to the conventional cooking methods (Engchuan, Jittanit & Garnjanagoonchorn, 2014). According to the authors, the conventionally cooked meatballs had higher moisture content and larger pores than that of the ohmically cooked sample which weakened the protein structure and resulted in a softer pork meatball. The authors pointed out that higher consumer acceptability could be expected for ohmically cooked meatballs considering the strengthened texture. According to the literature, food consumers prefer meatballs with hard texture to the soft ones (Hsu & Chung, 1998). However, more investigation is required for different meatball formulations, process conditions, and the target markets to make sure that replacing the traditional cooking method with ohmic heating can enhance the overall sensory quality of the product. In a similar study, continuous ohmic cooking of meatballs at different voltage gradients and holding times revealed that process optimization can result in a product with desired textural properties. The authors pointed out that both inadequate process time and applied energy can result in a product with undesirable texture (Icier, Sengun, Turp & Arserim, 2014).

3.3 Seafood

Matsubara, Tanaka, Narita & Seki (2007) evaluated the quality of salted-dried salmon following an ohmic treatment. According to the authors, ohmic heating the salmon to 45°C for 5 min prior to salting process increased the product fragility and enhanced consumer acceptability. Another research team showed that ohmic heating of mussels at 90 °C, the frequency of 60 Hz and electric field intensity of 9 V/cm significantly decreased the maximum cutting strength (15.6 N) as compared to that of the conventional heating method (20.4 N). The authors concluded that higher denaturation of the myofibrillar proteins in the conventionally heated samples resulted in a greater cutting resistance of *Mytilus chilensis* (Bastías, Moreno, Pia, Reyes, Quevedo & Muñoz, 2015).

The feasibility of tilapia thawing by ohmic heating revealed that the texture of the defrosted fish by quick ohmic heating was similar to that of the fresh sample (Boonpupiphat, Khukutapan, & Jittanit, 2014). Authors proposed low-temperature ohmic treatment (up to 30 °C) as a time- and water- saving alternative to the traditional water thawing method. Similarly, it was reported that the texture of cooked shrimp by ohmic heating was similar to that of the steam cooking method (Lascorz, Torella, Lyng & Arroyo, 2016). According to the authors, shrimp size was an effective parameter in process design of traditional cooking method as the required cooking times of large shrimps were 55% more than the small ones. On the other hand, the required process time in ohmic heating was 40 seconds, regardless of the shrimp size. This means that a better texture uniformity could be expected by replacing the traditional steam cooking method with the ohmic process. This advantage can make the ohmic heating as the preferred method for cooking a non-uniform bulk of shrimps or similar products to reach a uniform and desired textural characteristic within the entire sample (Lascorz, Torella, Lyng.& Arroyo, 2016).

A poor gel quality (shear stress of 15 kPa) was observed in the Pacific whiting surimi when it was prepared at slow heating rate by conventional heating method while rapid ohmic treatment resulted in a surimi gel with a better gel structure (shear stress of 30 kPa) (Yongsawatdigul, Park, Kolbe, Dagga & Morrissey, 1995). Likewise, it was reported that slow conventional water bath heating of Pacific whiting surimi emulsion resulted in a poor gel quality, while the quick ohmic heating yielded a surimi product with significantly higher gel strength (Park, Yongsawatdigul & Kolbe, 1998). The authors pointed out that ohmic heating minimized actin and myosin degradation and produced a surimi gel with a continuous network structure. In a like manner, gelation of Pacific whiting surimi in presence of salmon blood plasma under ohmic heating showed that product formulation such as incorporation salmon blood plasma can affect penetration distance and breaking force of the resulted gel (Fowler & Park, 2015). This study highlighted the importance of ohmic process optimization in terms of product formulation in enhancing the textural quality of the final product. Likewise, ohmic cooking of Pacific whiting surimi gel at different heating rates (3, 60 and 160 °C/min) revealed that higher heating rates enhanced the hardness and cohesiveness of the product due to quick enzyme inactivation and preventing the proteolytic degradation of cathepsin L (Moon, Yoon & Park, 2017). Conversely, the hardness and cohesiveness of Alaska pollock surimi gels decreased when the ohmic process was performed at high heating rates. Alaska Pollock surimi contained high and low levels of ETGase and endogenous protease, respectively. According to the study, the heating rate affected the microstructure of the product and resulted in products with different textural properties. Furthermore, incorporation of diced carrot decreased the cohesiveness and hardness values of both Alaska Pollock and Pacific whiting surimi gels due to interfering with the heat transfer and disconnecting the cross-links between fish proteins. The study revealed that varying ohmic process conditions, such as heating rate, and product formulation, such as protein source and addition of non-protein ingredients, can alter the textural properties of the ohmic-treated surimi gel (Moon, Yoon & Park, 2017).

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In a similar study, a surimi product (the mixture of Alaska Pollock surimi and potato starch) was subjected to ohmic heating at the voltage gradient of 4.3-15.5 V/cm and frequencies of 0.055- 20 KHz. The results showed that both product formulation and process condition (applied frequency and voltage gradient) affected the textural properties of the final product. At the voltage gradient of 4.3 V/cm and frequency of 55 Hz, increasing starch concentration from 0 to 9% decreased the gel strength from 128 to 33 kPa (at the moisture content of 75%), as starch granules prevented the mixture from forming a good gel matrix by absorbing water molecules and limiting the access of fish proteins to water . In addition, increasing the moisture content from 75% to 81% decreased the gel strength of pure surimi product from 128 to 54 kPa. The applied voltage and frequency were also shown to be effective parameters in the final texture of the surimi gel (Pongviratchai & Park, 2007). This study highlighted the importance of ohmic process optimization in terms of product formulation and instrumental conditions to produce a product with desirable textural properties.

An investigation on the texture of surimi gel under ohmic heating revealed that this volumetric heating produces a gel with higher gel strength as compared to that of the traditional water bath heating method (Chai & Park, 2007). Surimi batters containing different percentages of fish protein (*Theragra chalcogramma*), non-fish proteins (whey protein concentrates, Nutrilac, dried egg white, and beef plasma proteins), and potato and wheat starches were prepared and subjected to ohmic heating at 5 kHz the voltage gradients of 3.5 and 13 V/cm to reach the temperature of 85 °C. The torsion gelometer results showed that all ohmic processed samples had higher shear stress values than conventionally cooked ones. Ohmic heating quickly and volumetrically heats the product, resulting in short process time and uniform unfolding of myofibrillar proteins. On the other hand, heating of the surimi by water bath system is tedious and non-uniform. The authors pointed out that differences in time-temperature combinations and heating uniformity are the main reasons for textural differences between ohmic and conventional surimi products. Moreover, the applied voltage and product formulation was shown to be effective parameters in the gel strength of the surimi product. The authors proposed high voltage ohmic heating as an appropriate alternative to the traditional method of surimi production, considering the superior texture quality of the ohmic treated product (Chai & Park, 2007). This work also clearly demonstrated that ohmic heating can affect the microstructure of the product and result in a unique texture which is different from the conventional heated sample (Figure 4). According to the reported micrograph, the starch granules in the conventional cooking method showed a higher degree of gelatinization. In addition, increasing the input energy from 3.5 and 13 V/cm decreased the amount of gelatinized starch. This means that quick ohmic heating did not provide enough time for granules to be fully swelled and gelatinized. Therefore, more translucent gels were formed in the ohmic process through limited amylose molecules that leaked into the aqueous medium. This finding revealed that although fast volumetric heating can effectively accelerate some processes, such as sterilization, some of the time-dependent reactions, such as swelling of starch granules, cannot be accomplished during the limited times that this volumetric heating provides. Researchers may further explore the effect of variations in the microstructures of ohmically processed foods on the texture of these products.

3.4 Cereal related products

The feasibility of ohmic baking of cake and its effect on the textural properties of the final product was investigated and compared with the conventional cooking method. According to the Instron results, the firmness of the fresh cake after ohmic baking, which was crustless, was

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similar to that of the conventional baking process (about 2.5 N). However, the kinetic of textural changes of these two cakes over storage time was different. During 12 days of storage, the firmness of baked crumb by ohmic and oven increased to 6.7 and 9.9 N, respectively. Considering the moisture content distribution data, the authors suggested that the extensive moisture migration from crumb to crust of the oven baked cake was one of the main reasons of the hardened the crumb in a greater rate than the ohmic product which was crustless (Luyts, Wilderjans, Haesendonck, Brijs, & Delcour, 2013). Also, it is anticipated that moisture loss during the short ohmic baking was less than that of the long oven baking which resulted in higher moisture content of the ohmically baked cake after equilibrium or storage.

Ohmic cooking, as an innovative method, has also been used for bread baking. A study on the ohmic baking of bread revealed that the applied voltage and frequency can affect final product hardness. The author mentioned that optimized ohmic process can yield a bread sample with the same hardness as the oven baked bread (Maki, Yamaki, Tanaka, & Tanaka, 1998).

Gavahian et al. (2019) studied the effects of ohmic heating on the textural properties of rice grains (which were placed in the excess amount of water) and compared the results with those of microwave and conventional heating method (Gavahian, Chu, & Farahnaky., 2019). They reported that ohmic cooking resulted in greater softening rates as compared to those of other studied methods. It was reported that the texture of cooked rice by ohmic heating was different from that of electric rice cooker (Jittanit, Khuenpet, Kaewsri, Dumrongpongpaiboon, Hayamin & Jantarangsri, 2017). Cooking white and brown rice grains in the presence of appropriate amounts of water (water to rice ratio of 0.8:2.5) at the frequency of 50 Hz and electrical field strengths of 11-12 V/cm resulted in a rice grains with a lower hardness value (41 and 50 N, respectively) than the conventionally cooked one (47 and 60 N, respectively). The volumetric ohmic cooking method distributes heat inside the rice-water mixture uniformly and the starch gelatinization occurs throughout the rice grains simultaneously. On the other hand, a non-uniform distribution of heat is expected in the traditional rice cooker as it relies on heating surface and tedious modes of heat transfer, i.e. conduction and convection, which slows down the rice starch gelatinization and results in a product with lower gelatinization degree and higher hardness. The variation between the texture of ohmic and conventional cooked rice depends on the type of raw material (Jittanit, Khuenpet, Kaewsri, Dumrongpongpaiboon, Hayamin & Jantarangsri, 2017). Likewise, a higher degree of starch gelatinizing in the ohmic cooked rice than traditionally cooked one was reported by Yang, Chen, Sun, Li, & Liu (2006). These researchers found that ohmic cooked rice grains have a more porous microstructure than the conventionally cooked sample. According to the authors, electroporation was involved in that ohmic process and resulted in the structural changes (Yang, Chen, Sun, Li, & Liu, 2006). The occurrence of electroporation in ohmic treatment was comprehensively discussed elsewhere (Gavahian & Farahnaky, 2018; Gavahian, Chu & Sastry, 2018) and it is known that this phenomenon affects the cell membranes and enhance the diffusivity.

3.5 Other products

Ohmic heating of milk for paneer production resulted in a softer product than that of the conventional heating method with the hardness value of 312 gr and 410 gr, respectively. According to the authors, different heating mechanisms in ohmic and conventional methods affected the product microstructure and changed the final product texture (Kumar & Hausain, 2014). Variation in the microstructure of the ohmic treated product was also disused in **Sections 3.4** and **3.5** for surimi and rice.

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Soybean proteins (soymilk) were subjected to a two-stage ohmic heating process at the frequency of 50 Hz and the applied voltage of 200 V to produce tofu gel. The process was run at 70 °C for a defined period of time, followed by a second ohmic heating process at 100 °C. TPA revealed that replacing the traditional heating method by ohmic treatment increased the apparent breaking strength (the ratio of deformation at a breaking point to initial height) and Young's modulus (the ratio of apparent breaking strength to apparent breaking strain) by 12% and 16%, respectively. The reported data revealed that ohmic heating provides a better process control than the conventional steam heating method, which enables the food processors to define appropriate temperature-time combinations to enhance the product texture (Wang, Li, Tatsumi, Liu, Chen & Li, 2007).

4 Benefits and limitations of ohmic heating in textural softening

Previous studies have shown that ohmic heating is an effective way to reduce come-up time (Chiu,2002), total process time (Özkan, Ho & Farid, 2004), energy consumption (Farahnaky, Azizi & Gavahian, 2012), and produce uniform heat distribution (Bozkurt & Icier, 2010; Yildiz-Turp, Sengun, Kendirci, & Icier, 2013; Lascorz, Torella, Lyng& Arroyo, 2016) in processes that involves textural softening, such as cooking, as compared to that of the conventional methods. In addition, this innovative technique can minimize the textural damages of fragile vegetables during thermal sterilization (Eliot-Godéreaux, Zuber & Goullieux, 2001). Better process control () also enables the food processor to control and define the product texture precisely and stop the thermal process whenever necessary (Gavahian, Farahnaky, Shavezipur, & Sastry, 2016; Wang, Li, Tatsumi, Liu, Chen & Li, 2007). Some studies also claimed that ohmic heating can result in a product with better textural properties than the traditional heating procedures (Piette et al., 2004).

However, researchers raised several concerns for commercial application of this innovative textural softening technique including electrode corrosion and its potential negative effects on consumer health, high capital investment, operator safety, and non-uniform heating of some materials in the continuous mode of process.

As mentioned in **Section 3.3**, to reach desirable changes in some food materials, such as starch gelatinization, a longer process time than that of provided by high power ohmic heating may be required (Chai & Park, 2007). Therefore, a product with different nutritional and physical characteristics could be expected when traditional long processes are replaced with rapid ohmic heating. The health aspect of the ohmic heating process for cooking beef patties was studied by Wang and Farid (2015). The authors observed pitting corrosion on the ohmic electrodes after the cooking process and pointed out that this may affect the safety of the treated product. According to the authors, Ni and Cr ions transferred from the stainless steel electrodes to the meat at lower rates than Fe ion, leading to Ni and Cr ions concentrations in the cooked meat within the safe limit when high-frequency power is used. The authors concluded that process optimization, such as applying an appropriate frequency (10 kHz instead of 50 Hz) and using suitable electrodes can reduce the chemical changes in the ohmic processed product (Wang & Farid, 2015). Gavahian, Lee, and Chu (2018) also raised a concern about the potential negative effects of electrode corrosion on the final product in an ohmic process (Gavahian, Lee, & Chu, 2018).

The feasibility of continuous high-temperature short-time process of red bean samples by ohmic heating was investigated by Fillaudeau, Winterton, Kesteloot, Duquesne, Leuliet & Legrand (2007). According to the results, beans lost their elastic properties during ohmic heating in close correlation with water content. The maximal stress was also decreased sharply over the process time. However, the authors reported a high standard deviation in the textural properties of the cooked beans which can be translated to the high heterogeneity of the product. The authors concluded that continuous ohmic process of this legume is not feasible due to the high variations in the textural properties of the processed product. According to the authors, variation in the product homogeneity (due to volume expansion), enhanced physical degradation of particles (due to loss of mechanical properties), quality degradation of duct plugging (due to the large size of beans), and instability of electrical conductivity (which vary with particle concentration and temperature) are among the limiting parameters for continuous ohmic textural softening of the red bean (Fillaudeau, Winterton, Kesteloot, Duquesne, Leuliet & Legrand, 2007). Furthermore, the possibility of enhanced leaching of the cell constitutes during an ohmic process should be taken into account. It was reported that ohmic heating process, especially at low frequencies, can affect the cell membranes of fresh produce through electro-thermal effects (Gavahian & Farahnaky, 2018; Gavahian, Chu & Sastry, 2018). The release of cell material to the heating medium could be undesirable for some products and processes as it could be translated to nutrition loss and increased biochemical oxygen demand (BOD) of the effluent. Moreover, the capital investment (Gavahian, Chu & Sastry, 2018) and safety issues (Ramaswamy, Marcotte, Sastry & Abdelrahim, 2014; Gavahian & Farahnaky, 2018) are among the drawbacks of this alternative heating method.

5. Summary and future prospects

Ohmic treatment can influence the micro- and macro- structures of the foodstuff through thermal and non-thermal effects. While the thermal effects of the ohmic process on food and cell structures are widely studied, there are limited data on the non-thermal effects of this technique on food texture, especially when these non-thermal effects are overshadowed by exposing the product to high temperatures in several processes such as cooking and sterilization. A more in-depth study is necessary to fully understand both thermal and non-thermal effects of ohmic heating at different process conditions and for different food materials. Ohmic heating provides food industries with several benefits such as saving in process time and energy. In addition, this technique offers a good and reliable process control, as compared to the traditional methods. These benefits make ohmic heating a superior alternative to the traditional process. However, it should be noted that heating food materials volumetrically and at a higher rate than the conventional process can affect the kinetic of textural softening and the product texture. Therefore, optimization of the ohmic process conditions, including electrical specification, process time, and temperature, as well as product formulation are among the considerations to achieve a final product with desirable texture characteristics. In addition, several researchers raised concern about the safety and feasibility of industrial applications of this method for some products due to the complexity of this process in continues production. These along with the high capital investment are among the main challenges in the industrial adaptation of this technique. To this date, several studies used instrumental methods to evaluate the effects of ohmic heating on food texture. However, to evaluate the feasibility of commercial ohmic process from the consumer perception point of view, further sensory evaluation studies along with the instrumental testing is suggested.

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Tables

Table 1- Summary of main findings on the effect of ohmic heating on the texture of food materials

Commodity	**Treatment purpose**	**Process condition**	**Method of texture study/Studied parameter**	**Key observation**	**Reference**
Cauliflower	Thermal processing	T: 135 F: 50 Hz P: 3.6 PT: 0.5	A developed textural measurement cell/ firmness	RMI.	(Eliot-Godéreaux, Goullieux & Pain, 1999)
Cauliflower	Sterilization	T: 121 P: 10 PT: 3 FR: 100	TPA/ maximum force of compression, total work of compression	RMI	(Eliot-Godéreaux, Zuber & Goullieux, 2001)
Red beet, carrot, and golden carrot	Cooking (textural softening)	T: 100 F: 50 V:220, 380 PT: 0-19	TPA/ hardness, gradient and compression energy	ohmic heating resulted in greater softening rates. POI RMI	(Farahnaky, Azizi & Gavahian, 2012)
Radish, turnip, potato, cabbage	Cooking (textural softening)	T: 100 F: 50 V:220, 380 PT: 0-90	TPA/ Hardness, gradient, compression energy, Springiness, gumminess, chewiness	greater textural softening rate follow the ohmic cooking RMI	(Kamali & Farahnaky, 2015)
Potato, carrot and apple	Cooking (textural softening)	T: F: 50 E:11, 22, 33 PT: 1,2,3,4	TPA/ firmness	POI RMI	(Olivera, Salvadori & Marra, 2013)
Tomato	Peeling	T:100 F: 60 V:0-1000 E:6.45-64.5 PT: 0.3-	Manual compression tester/ firmness	Both process and post-process condition can affect the texture of an ohmic-treated sample.	(Wongsa-Ngasri & Sastry, 2016)

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		6.3			
Apple	Pretreatment for osmotic dehydration	T: 85 F: 50 E:66 PT: 1	TPA/firmness	POI Both thermal and non-thermal effects of ohmic heating affect the texture of product.	(Allali, Marchal & Vorobiev, 2010)
Apple	Impregnation to produce an enriched snack	T: 30, 40, 50 F: 60 V:100 E:13 P: PT: 0-105	TPA/firmness	Ohmic heating enhanced the folic acid content of the final product due to the electropermeabilizatio n POI	(Moreno, Espinoza, Simpson, Petzold, Nuñez & Gianelli, 2016)
Apple	Pretreatment for osmotic dehydration	T:30,40, 50 F: 60 E:13 PT: 300	TPA/firmness	Non-thermal effects of ohmic treatment enhanced the firmness of samples by leaching the cell constitutes and dehydration of the apple	(Moreno, Simpson, Estrada, Lorenzen, Moraga & Almonacid, 2011)
Carrot	Shelf life enhancement	T:40 F: 1,60 V:120 E:33.3	TPA/ hardness, Fracturability, adhesiveness, cohesiveness and chewiness	The non-thermal effects of ohmic heating affected the textural properties of the product.	(Bhale, 2004)
Pineapple	Shelf life and quality enhancement	T: 60, 70, 80 F: 50 E: 20, 30, 40 PT: 1	TPA/ firmness	Ohmic heating deactivated the enzymes and reduced the textural changes during storage	Pham, Jittanit & Sajjaanantakul (2014)
Potato	Thawing	T:-18-+4 E: 25	TPA/ firmness, elasticity, stickiness	Ohmic heating enhanced the firmness of the product. pretreatments can affect the degree of textural softening in an ohmic process RMI	(Icier, Cokgezme & Sabanci, 2017)

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Beef cuts	Thawing	T: −18-+10 F: 50 E: 10, 20, 30	TPA/ hardness, springiness, cohesiveness, gumminess, chewiness and resilience	Both thermal and non-thermal effects of ohmic heating could be involved in meat thawing process	(Icier, Izzetoglu, Bozkurt & Ober, 2010)
Ham Emulsions	Cooking	T: 60, 70, 8O F: 60 V:40-100 PT: 0, 20 30	TPA/ hardness, Cohesiveness, springiness, gumminess, and chewiness	Higher temperatures, shorter come-up times, and longer holding times resulted in a softer texture Ohmically cooked hams had a softer and chewier texture	(Chiu, 2002)
Bologna emulsion	Cooking	T: 70 , 75 , 80 V: 64, 76, 103 PT: 0-15	TPA/ hardness (N), cohesiveness, springiness, and resilience	The ohmic product was softer, less cohesive, and less resilient	(Piette et al., 2004)
Frankfurters	Cooking	T:73 F: 50 E: 3, 5, 7 PT: 2	TPA/ Hardness, Springiness, Cohesion, Gumminess, Chewiness	Ohmic cooking yielded a less elastic and mushier product.	(Shirsat, Brunton, Lyng, & McKenna, 2004)
Burger patties	Cooking	T:70 F: V:50 PT: 2	Compression test/ compressive stress, elastic contact stiffness, elasticity index	Ohmic cooking yielded a product with similar textural properties to that of classical method.	(Özkan, Ho & Farid, 2004)
Beef muscles	Cooking	T: 72 F: 50 V: 25, 50 PT: 12	Warner–Bratzler/ shear force	Ohmic heating yielded a product with a tougher texture. PTI in textural characteristics and textural uniformity.	(Zell, Lyng, Cronin & Morgan, 2009)
Pork	Cooking	T:20-100 F: 50 E:10 PT: 3-11	Warner–Bratzler/ shear force	Increasing the end point temperature enhanced the Warner-Bratzler shear force of ohmically treated samples	(Dai, Zhang, Wang, Liu, Li & Dai, 2014)

Ground beef	Cooking	T: 70 F: 50 E:20, 30, 40 PT: 0-0.8	Warner–Bratzler/ firmness and toughness values	Ohmic cooking increased the firmness of the product	(Bozkurt & Icier, 2010)
Turkey meat	Cooking	T:72, 95 F: 50 V: 100 E:8.3 PT: 4, 5	TPA/ Hardness, cohesiveness, springiness, gumminess and chewiness	Running ohmic cooking at the high-temperature-short time condition increased product firmness.	(Zell, Lyng, Cronin & Morgan, 2010)
Beef muscle	Cooking	T:72 E:3.3, 12 PT: 4, 17	Texture analyzer with a blade/ Shear force value	Ohmic product had a lower Shear force value due to higher degradation of major structural proteins.	(Tian et al., 2016)
Pork meatballs	Cooking	T:80 F: 50 V: 72 E:20 PT: 1.5	TPA/ firmness (yield strength)	Ohmic cooked meatballs had lower moisture content and smaller pores which strengthen the protein structure and resulted in a firmer meatball. Ohmic cooking increased product acceptability	(Engchuan, Jittanit & Garnjanagoonchorn, 2014)
Beef meatballs	Continuous ohmic cooking	T:75 F: 50 E:15, 20, 25 PT: 0, 0.25, 0.5	TPA/ hardness, chewiness, gumminess, springiness and resilience	POI Inadequate process time and applied energy can result in a product with undesirable texture	(Icier, Sengun, Turp & Arserim, 2014)

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Chilean blue mussel	Cooking	T: 50,70,90 F: 60 V:70 E: 9.15 PT: 4	Texturometer/ maximum cutting strength	The lower denaturation of the myofibrillar proteins in the ohmically heated samples resulted in a lower cutting resistance of the product	(Bastías, Moreno, Pia, Reyes, Quevedo & Muñoz, 2015)
Shrimp	Cooking	T: 72 F: 50 V: 120	Instron Universal Testing machi/Warner-Bratzler shear force, Kramer	Unlikeconventional process, shrimp size was not an effective parameter in ohmic process design. Ohmic heating improved texture uniformity	(Lascorz, Torella, Lyng & Arroyo, 2016)
Pacific whiting surimi	Gelation	T: 55 F: 60 V:200 E: 13.3 PT: 0,1,3,5	Torsion failure tests/ Shear stress and shear strain	Shear stress and shear strain of ohmically heated surimi was two times more than conventionally gel. Ohmic heating minimized degradation of myosin and actin resulting in a continuous network structure.	(Yongsawatdigul, Park, Kolbe, Dagga & Morrissey, 1995)
Pacific whiting surimi	Gelation	T: 90 F: 10k V:250 E: 12.6	Fracture gel evaluative/ breaking force, penetration distance	POI	(Fowler & Park, 2015)
Alaska pollock surimi (contains carrot)	Gelation	T: 90 E: 3.3, 12, 17.3	TPA/ hardness, cohesiveness	POI such as heating rate. RMI such as product formulation (protein source and addition of non-protein ingredients)	(Moon, Yoon & Park, 2017)
Alaska Pollock surimi (contains potato starch)	Gelation	T:80 F: 55,5k, 20k V:60,220 E: 4.3,15.5	Fracture gel evaluative/ gel strength (shear stress), gel cohesiveness (shear strain)	POI RMI (product formulation)	(Pongviratchai & Park, 2007)
Alaska pollock surimi (contains starches and	Gelation/cook	T: 50	Fracture gel evaluative/ gel	The texture of ohmically processed	(Chai & Park,

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protein additives)	ing	F: 5k V:55,200 E: 3.5, 13	strength (shear stress), gel cohesiveness (shear strain)	product was different from the conventionally treated one. Rapid ohmic heating did not provide enough time for granules to be fully swelled and gelatinized.	2007)
Pound cake	Baking	T: 100 PT: 55	Instron (Compressing test)/ firmness	Ohmic heating produced a crustless cake with the same firmness as the conventional baking. Less changes in the firmness of ohmic backed cake was observed over the storage time, as compared to oven baked cake.	(Luyts, Wilderjans, Haesendonck, Brijs, & Delcour, 2013)
Rice	Cooking	T: 100 F: 50 V: 45, 50 E: 10.7, 11.8 PT:28,49	TPA/ hardness, adhesiveness, cohesiveness, springiness, gumminess, chewiness	Ohmically cooked rice had a different texture, as compared to that of electric rice cooker	(Jittanit, Khuenpet, Kaewsri, Dumrongpongpaiboon, Hayamin & Jantarangsri, 2017)
Tofu	Thermal denaturation	T: 95, 100 F: 50 V: 200	TPA/ Apparent breaking strength, Apparent Young's modulus	Ohmic treatment increased the apparent breaking strength and Young's modulus and provided a better process control	(Wang, Li, Tatsumi, Liu, Chen & Li, 2007)

* T: temperature(°C); F: frequency (Hz); V: Voltage (V); E: Electric field strength (V/cm);P: Input Power (kW); PT: process time (min); FR: Flow rate (kg/h); TPA: Texture profile analysis; RMI: raw material importance (selecting appropriate raw materials can important consideration in enhancing textural quality of the ohmically processed food); POI: process optimization importance (process optimization is an important consideration to achieve the desired texture in an ohmic treatment); PTI: pre-treatment importance

Table 2- Materials that used as ohmic electrodes in the research involving textural modifications of food materials.

Electrode	**Cell type**	**Treated food**	**Media**	**Reference**
Stainless (304) steel	Teflon	Red beet, carrot, and golden carrot	NaCl solution	(Farahnaky, Azizi & Gavahian, 2012)

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	(304)	Teflon	Radish, turnip, potato, cabbage	NaCl solution	(Kamali & Farahnaky, 2015)
	(316)	Teflon	Beef muscle	NS	(Tian et al., 2016)
	(316)	Teflon	Pork	NS	(Dai, Zhang, Wang, Liu, Li & Dai, 2014)
	(316L)	Glass	Pineapple	$CaCl_2$ solution contains ascorbic acid	Pham, Jittanit & Sajjaanantakul (2014)
		plastic	Apple	Sucrose solution	(Moreno, Simpson, Estrada, Lorenzen, Moraga & Almonacid, 2011)
		Pyrex	Ground beef	NS	(Bozkurt & Icier, 2010)
		acrylic	Pork meatball	NaCl solution	(Engchuan, Jittanit & Garnjanagoonchorn, 2014)
		Teflon	Lean beef meatball	NS	(Icier, Sengun, Turp & Arserim, 2014)
		Plastic	Chilean blue mussels	NaCl solution	(Bastías, Moreno, Pia, Reyes, Quevedo & Muñoz, 2015)
		NR	Shrimp	NaCl solution	(Lascorz, Torella, Lyng & Arroyo, 2016)
		PVC	Pacific Whiting Surimi	NaCl solution	(Yongsawatdigul, Park, Kolbe, Dagga & Morrissey, 1995)
		Plexiglass	Pound cake	NS,	(Luyts, Wilderjans, Haesendonck, Brijs, & Delcour, 2013)
		Glass	Rice	NaCl solution	(Jittanit, Khuenpet, Kaewsri, Dumrongpongpaiboon, Hayamin & Jantarangsri, 2017)
		plastic	Apple	Apple juice contained folic acid, potassium sorbate and calcium chloride	(Moreno, Espinoza, Simpson, Petzold, Nuñez & Gianelli, 2016)
Aluminum		Teflon	Potato, carrot and apple	NR	(Olivera, Salvadori & Marra, 2013)

Titanium	Pyrex glass	Tomatoes	NaCl/NaOH mixture	(Wongsa-Ngasri & Sastry, 2016)
	NR	Carrot	NS	(Bhale, 2004)
	Nylon	Ham emulsion	NS	(Chiu, 2002)
	Nylon	Bologna emulsion	NS	(Piette et al., 2004)
Platinum-coated titanium	Teflon	Frankfurter emulsion	NS	(Shirsat, Brunton, Lyng, & McKenna, 2004)
	Polytetrafluoroethylene	Whole beef muscle	NS	(Zell, Lyng, Cronin & Morgan, 2009)

* T: temperature(°C); F: frequency (Hz); V: Voltage (V); E: Electric field strength (V/cm); PT: process time (min); NR: not reported; NS: no solution (sandwiched between electrodes)

Figures

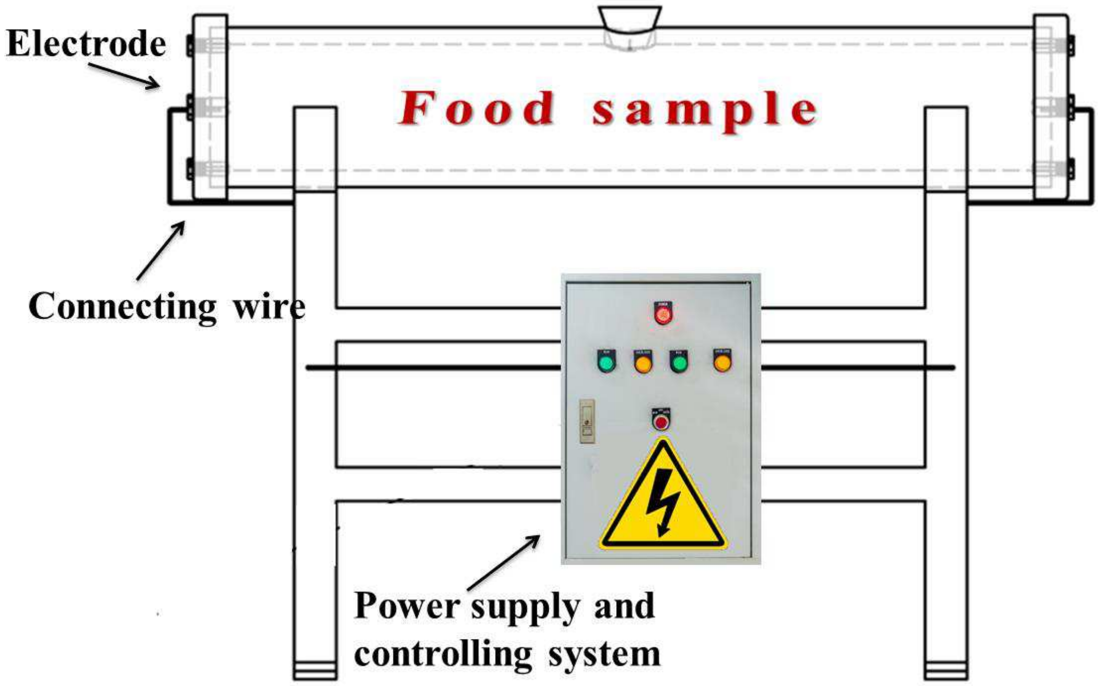

Fig 1- The schematic representation of a batch ohmic system for textural softening, cooking or backing of food commodities. The food sample can either be immersed in an electroconductive solution or be sandwiched between electrodes.

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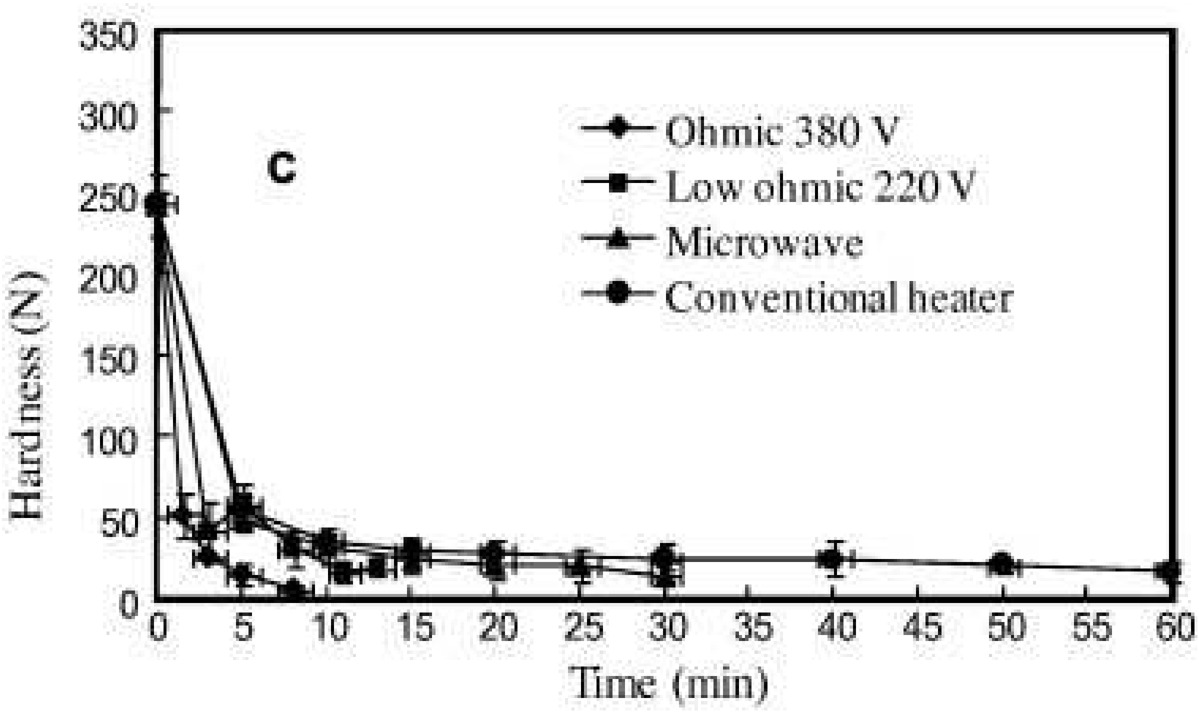

Fig. 2- Variations in the hardness of golden carrot over process time in ohmic (high and low power intensity), microwave, and water conventional heating systems (Farahnaky, Azizi & Gavahian, 2012)

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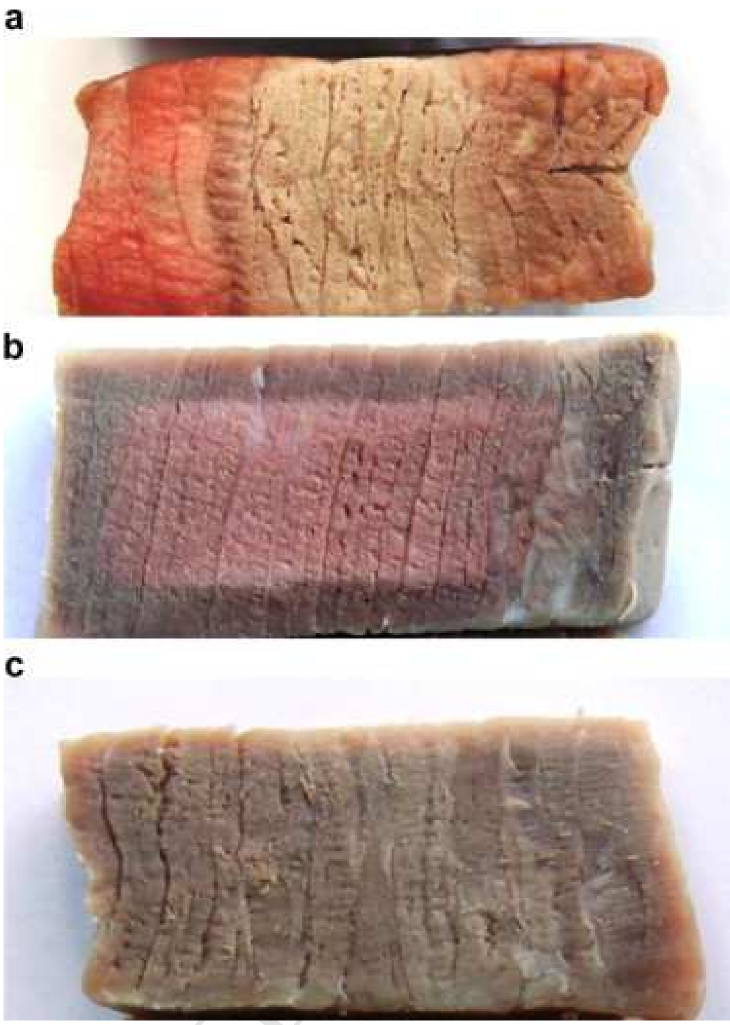

Fig. 3-.Pretreatment conditions can affect the texture uniformity of an ohmic treated product (a) center injection of salt (b) two days soaking in salted water and (c) multi-injection and extended soaking in brine. The pink color (light monochrome) indicates under-processing area which is expected to have the similar texture to the unprocessed meat while the dark monochrome area are fully cooked by ohmic heating and have different textural values from the unprocessed samples (Zell, Lyng, Cronin & Morgan, 2009)

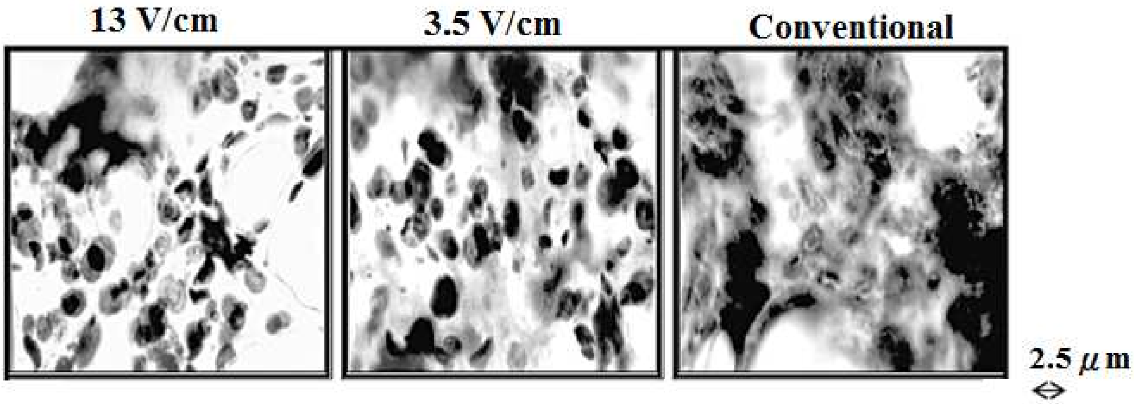

Fig. 4- The effects of heating method and voltage gradient on microstructure of surimi as compared to that of conventional heating method (Chai & Park, 2007)

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Highlights

- Ohmic treatment can modify textural properties of food materials
- This process can shorten the process time and reduce consumed energy
- Both thermal and non-thermal effects of ohmic treatment can alter the product texture
- Pretreatments, raw material, and process condition affect the product texture.
- The high capital investment and safety concerns and are among the obstacles for its industrial adaptation.

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